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Technologies for remote lidar sensing of the surface to detect low concentrations of hydrocarbons in Siberia and the far north

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Abstract. The results of research in the field of remote sensing using the technologies of radar and laser detection of hydrocarbons raw materials aimed at the search, localization and topographic location of discovered oil and gas field, the determination of leaks and atmospheric pollution by hydrocarbon gases (e.g. methane) are presented. The main problems with sounding are revealed. To determine the extremely low concentrations of methane in the atmosphere, the main constraining factors were determined and the need to suppress side interference arising on the probing path of the laser beam was shown. To formulate requirements for the sensitivity of equipment and the accuracy of software calculations, the choice of a mathematical model of the path of the laser beam is justified. A modification of the known model is proposed to represent the lidar path based on the differential absorption method taking into account correction coefficients of molecular and aerosol absorption and scattering. Thus, the presented model is a set of methods for providing more accurate and localized data for the implementation of a hardware-software complex.

1. Introduction

A significant problem in the exploration of oil fields in the region of Siberia and the far north is the inaccessibility and extremely low temperatures, which reduces the rate of discovery of new deposits. A number of approaches are known for solving the indicated problem [1–3].

One of the most promising methods is the exploration method based on the use of remote lidar sensing technologies for the surface layer from an aircraft, which makes it possible to detect extremely low concentrations of hydrocarbons [4]. By detecting stable areas with a high content of suspended solids in the atmosphere, fixing local natural gas outlets, observing the spatial dynamics of surface leaks in real time, it becomes possible to topologically link the proposed deposits to the terrain.

Existing laser-location methods [5,6] are used everywhere for shooting and detecting gas pipeline leaks and solving topographic problems, which allows obtaining results in a wide range of subject areas. However, the known methods and hardware are designed to determine large concentrations of hydrocarbons (up to 1 ppm) [5]. However, for the localization of prospective deposits, it is necessary to determine the extremely low gas content in the surface space.

A solution to this problem can be obtained using a lidar based on the differential absorption method with high selectivity, which is provided by a set of technical solutions [7]. First of all, the functional composition of the lidar hardware should allow generating and efficiently receiving laser radiation at appropriate wavelengths that are close in their values to absorbed octanes and exclude the possibility

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of spurious solar illumination. Secondly, at the hardware and software level, it is necessary to solve filtering, noise reduction, and isolating the received useful signal with high selectivity. This requires the development of an adequate mathematical representation of the propagation path of the laser beam. Such a model will allow you to take into account the main factors affecting the accuracy of the processing of the useful signal, namely: type of landscape, signal dispersion, limitation of signal reception distance.

In order to solve the problems of signal scattering and develop a list of requirements for the developed complex, a mathematical apparatus is proposed that describes the path of the light beam.

2. Mathematical model

According to the authors of [4–6,8], the following representation of the lidar equation (1) is the most accurate for this case:

$$P_\lambda(R) = P_0\eta(\frac{c\tau}{2})A(R)\frac{\beta_\lambda(R)}{R^2}\exp[-2\int_0^R \alpha_\lambda(x)\mathrm{d}x], \quad (1)$$

R is the distance to the scattering volume; c is the speed of light; τ is the laser pulse duration; P_λ is the power of the scattered radiation obtained during the time $t = \frac{2R}{c}$; P_0 is the laser power; η is the receiver efficiency (calibration constant); λ is the wavelength of the laser radiation; β_λ is the volume coefficient of backscattering of the atmosphere; A is the effective area of the receiver; α_λ – volume coefficient of attenuation (extinction) of the atmosphere.

The coefficients of molecular scattering (β_λ^{mol}) and attenuation (α_λ^{mol}) can be calculated with good accuracy based on the Rayleigh scattering theory [9], or using a specific model of the atmosphere [8]. For a correct estimation of the transmission of laser radiation by the atmosphere, information is needed on the physical and optical models of the atmosphere. One of the most complete for solving the tasks of remote sensing seems to be a physical model of the atmosphere developed at the V E Zueva SB RAS [4]. In addition to data on temperature, pressure, and concentration of H_2O and O_3 for various climatic zones, it contains information on the altitude distribution of CO_2, CO, CH_4, N_2O, NO, NO_2, as well as information on their standard deviations for various heights.

The theory of molecular scattering of Rayleigh light gives the following expression (2) for the volume coefficient of backward molecular scattering (in cm-1 * sr-1) in gases:

$$\beta_\lambda^{mol} = \frac{\pi^2(n^2-1)^2}{N^2\lambda^4}\frac{6+3\Delta}{6-7\Delta 0}, \quad (2)$$

N is the parameter of concentration of molecules; n is the refractive index; Δ is the degree of depolarization scattered radiation.

For mixture of atmospheric gases at altitudes up to 100 km, expression (2) describes the volume coefficient of backscattering, and will have form:

$$\beta_\lambda^{mol} = 5.45\cdot 10^{-28} N(\frac{550}{\lambda})^4,$$

where λ is taken in nanometers. Considering a single molecular scattering it has parameter Δ, which is associated with the polarization anisotropy of the molecules. For example, such as monatomic gases of the argon type, it is equal to zero (for air, Δ = 0.035, and for nitrogen Δ = 0.036) in the case of isotropic scattering centers.

The coefficients of aerosol scattering (β_λ^{aer}) and attenuation (α_λ^{aer}) can be determined either theoretically. It is based on the theory of aerosol scattering (Mie theory) [9], or experimentally (from lidar signals). It is based on algorithms of solving the lidar equation, which are detailed considered in a number of papers [10].

According to the theory of scattering of electromagnetic waves by aerosol particles in the approximation of dielectric spheres (Mie theory), one can obtain expressions for the volume scattering coefficients (3) and attenuation (4) at a given wavelength:

$$a^{aer}(n,\lambda) = \int_0^\infty \pi r^2 Q_{ext}(p,n,\lambda) f(r)\mathrm{d}r\,, \tag{3}$$

$$\beta^{aer}(n,\lambda) = \int_0^\infty \pi r^2 Q_{scat}(p,n,\lambda) f(r)\mathrm{d}r\,, \tag{4}$$

r is the radius; $f(r)$ are size distribution functions of aerosol particles; n' is the complex refractive index of the dielectric sphere; Q_{ext} and Q_{scat} are the scattering and attenuation efficiency coefficients; $p = \dfrac{2\pi r}{\lambda}$ is the relative particle size.

In [6], aerosol attenuation is described by the empirical expression (5):

$$\alpha^{aer} = \frac{3.912}{R_m}\left(\frac{\lambda}{0.55}\right)^q, \tag{5}$$

where R_m is the meteorological range of visibility at $\lambda = 0.55$ μm.

The values of R_m for various visibility conditions are known [9], and the coefficient q is given by the following expression (6):

$$q = \begin{cases} 0.585(R_m)^{1/3}\, R_m \le 6\,km \\ 1.36\,km \le R_m \le 5\,km \\ 1.6 R_m \ge 50\,km \end{cases}, \tag{6}$$

When developing a hardware-software complex of a lidar for an aviation platform (Figure 2), it should be taken into account that the parameter $A(R)$ in equation (1) can be determined only by the characteristics of the receiver and transmitter. It depends on the spatial distribution of power in the laser beam, as well as the degree of overlap of the laser beam and the field of view of the telescope. This factor takes into account the influence of the shadow of the secondary mirror of the telescope, the aberration of the optical system, the inhomogeneity of the surface of the detector and the effective area of the telescope. When determining the size of the telescope mirror, it should be taken into account that the effective receiver area $A(R)$ is given by the following expression (7):

$$A(R) = \frac{A_0}{\pi W^2(R)} \times \int_{r=0}^{r_{\max}} \int_{\psi=0}^{2\pi} \xi(R,r,\psi) F(R,r,\psi) r\mathrm{d}r\mathrm{d}\psi = A_0 \xi(R)\,, \tag{7}$$

$F(R,r,\psi)$ is the spatial distribution function of the laser radiation intensity; $\xi(R,r,\psi)$ is the geometric probability coefficient; ψ is the azimuthal angle; $W(R)$ is the size of the laser spot at a distance R; A_0 is the area of the entrance aperture of the telescope; $\xi(R)$ is the function of the geometric factor (FGF) of the lidar, which takes into account the degree of interception of the laser beam reflected from the target.

The developed hardware-software complex for controlling lidar uses the principle of differential absorption (DP), based on the phenomenon of resonant absorption of laser radiation inside the absorption line of the studied gas. The gas concentration is calculated using beam signals at two close frequencies, one of which is inside the absorption line, and the other outside it.

Using lidar equation (1) for elastic scattering at wavelengths λ_{on} and λ_{off}, from the power ratios of the reflected signals P_{on} and P_{off} at two wavelengths, we obtain the following expression (8) for the concentration of the molecules under study.

$$N(R) = \frac{-1}{2\Delta\sigma}\frac{\partial}{\partial R}\left[\ln\frac{P_{on}(R)}{P_{off}(R)}\right] + \frac{1}{\Delta\sigma}\frac{\partial}{\partial R}\left[\ln\frac{\beta_{on}(R)}{\beta_{off}(R)}\right] - \frac{\alpha_{on}(R) - \alpha_{off}(R)}{\Delta\sigma}, \quad (8)$$

β_{on} and β_{off} are the coefficients of backscattering of the atmosphere at wavelengths λ_{on} and λ_{off}; α_{on} and α_{off} are the attenuation coefficients of the atmosphere for the waves λ_{on} and λ_{off};

$$\Delta\sigma = \sigma(\lambda_{on}) - \sigma(\lambda_{off}) = \sigma_{on} - \sigma_{off}, \quad (9)$$

$\Delta\sigma$ is the cross section of the DP (differential absorption); $\sigma(\lambda_{on})$ and $\sigma(\lambda_{off})$ are the effective absorption cross sections at two wavelengths. In the case of a surface sensing path, $\sigma(v)$ for a line with a central frequency v_0 is well described by the Lorentz contour [4–5] shown in expression (10):

$$\sigma_L(v) = \frac{S}{\pi}\frac{\gamma_L}{\gamma_L{}^2 + (v - v_0)^2}, \quad (10)$$

S, γ_L are the intensity (12) and half-width (11) of the absorption line, respectively, which for vibrational-rotational lines at pressure p and temperature T have the following form:

$$\gamma_L(T, p) = \gamma_L^0 (\frac{T_0}{T})^l \frac{p}{p_0}, \quad (11)$$

$$S(T) = S_0\left(\frac{T_0}{T}\right)^m \exp\left[-E^n \frac{hc}{kT}(\frac{1}{T} - \frac{1}{T_0})\right], \quad (12)$$

$\gamma_L{}^0$ and S_0 are the Lorentz an half-widths and intensities at temperature T_0 and pressure p_0; E^n is the energy of the lower vibrational-rotational state; h is Planck's constant; k is the Boltzmann constant; m and l are the parameters of the temperature dependence of the half-width and intensity, respectively. The parameter l for various gases can vary from 0.5 to 1, the parameter $m = 1$ for linear molecules and 1.5 for nonlinear ones.

Expression (8) shows the possibility of restoring the continuous profile $N(R)$ during continuous recording of lidar signals. However, in practice, lidar signals will be recorded by the receiving equipment in the form of a discrete digital data array obtained at equal time intervals Δt, which corresponds to the spatial resolution $\Delta R = \frac{c\Delta t}{2}$. Then, from (8) for signals received from atmospheric objects remote along the sensing path at a distance of R and $R+\Delta R$, the expression for the average concentration (13–15) of the studied gas in the indicated range of distances follows:

$$N' = \frac{-1}{2\Delta\sigma\Delta R}\ln\left[\frac{P_{on}(R+\Delta R)}{P_{off}(R+\Delta R)}\frac{P_{off}(R)}{P_{on}(R)}\right] - \frac{\alpha_{on}^{mol} - \alpha_{off}^{mol}}{\Delta\sigma} + B_S + E_a, \quad (13)$$

$$B_S = \frac{-1}{2\Delta\sigma\Delta R}\ln\left[\frac{P_{on}(R+\Delta R)}{P_{off}(R+\Delta R)}\frac{P_{off}(R)}{P_{on}(R)}\right] - \frac{\alpha_{on}^{mol} - \alpha_{off}^{mol}}{\Delta\sigma} + B_S + E_a, \quad (14)$$

$$E_a = \frac{-\alpha_{on}^{aer} - \alpha_{off}^{aer}}{\Delta\sigma}, \quad (15)$$

When calibrating the transmitting and receiving equipment of the complex, the wavelengths should be chosen so that the coefficients of backscattering and attenuation of the atmosphere are independent of the wavelength. Therefore, the spectral interval between two wavelengths should be so small that the terms B_s and E_a can be neglected. Then the expression for concentration is simplified:

$$N' = \frac{-1}{2\Delta\sigma\Delta R}\ln\left[\frac{P_{on}(R+\Delta R)}{P_{off}(R+\Delta R)}\frac{P_{off}(R)}{P_{on}(R)}\right], \tag{16}$$

Based on the foregoing and the results of preliminary experiments [11–13] in the problem area, it was noted that the obtained equation (16) adequately describes the depend of the concentration of desired gas on the reflected radiation power at two wavelengths λ_{on} and λ_{off}. In this case, λ_{on} is inside the absorption line of the desired gas, and λ_{off} is outside it (Figure 1).

To assess the sensitivity of the developed equipment – the maximum allowable values of atmospheric gas concentrations N_{min}, which can be detected with a minimum measurement error of optical signals, it is convenient to use the formula proposed in [6]:

$$N_{\min}(R) = \frac{1}{\Delta\sigma\Delta R}\frac{2}{SNR(R)}, \tag{17}$$

SNR is the signal-to-noise ratio at a distance R from the lidar.

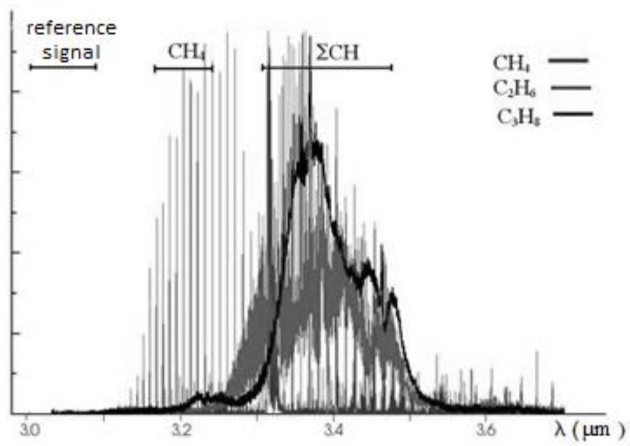

Figure 1. The spectra of the determined hydrocarbons and the spectral ranges selected for measuring their concentrations [14].

Thus, to increase the sensitivity of the device at a given spatial resolution ΔR, one should choose the most intense absorption lines of the gas under investigation with a maximum DP cross section $\Delta\sigma$.

3. Conclusions

The initial assumption that it is possible in principle to create a lidar to determine exactly the maximum concentrations of hydrocarbons in the surface layer is confirmed by simulation results. It was determined that the proposed architecture, the main parameters of the equipment and the differential absorption method are effective for remote sensing on paths not exceeding 200 m.

When setting the lidar to determine the octane group gases by the differential absorption method, wavelengths should be used for which the ratio $\frac{\Delta\sigma}{\Delta\lambda}$ is maximum, where $\Delta\lambda = \lambda_{on} - \lambda_{off}$ Δ. It can be seen from expression (17) that, at significant signal-to-noise ratios, the concentration of N_{min} is limited by the systematic error of the lidar, which can be from 10 to 20 %.

Currently, the mathematical apparatus proposed for calculating the concentration of saturated hydrocarbons along the lidar route requires adequate algorithmic representation and modeling, software development for a microprocessor-based lidar control system, and a series of field experiments.

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